DEVELOPMENT OF AN EMBEDDED SYSTEM FOR MONITORING ELECTROPHYSIOLOGICAL SIGNALS FROM TOMATO PLANTS IN SMART AGRICULTURE

Pham Van Khoa[1*], Dinh Tien Dung[1], Nguyen Ngo Lam[1], Chi-Chia Sun[2]
[1]*Ho Chi Minh City University of Technology and Education, Vietnam*
[2]*National Taipei University, Taiwan*

ARTICLE INFO

Received: **05/02/2025**
Revised: **13/4/2025**
Published: **15/4/2025**

KEYWORDS

Terms— IoT
Phytosensing
Tomato plant electrophysiology
Sensors
Embedded system

ABSTRACT

This study was conducted to address the increasing issue of environmental pollution, which negatively impacts agricultural crops, particularly tomatoes - a high-value crop widely cultivated in Vietnam. The objective of this research is to develop an intelligent embedded system that utilizes a microcontroller integrated with electronic circuits and electrodes to monitor the physiological responses of tomato plants to environmental factors such as light, temperature, and humidity. This system incorporates amplifiers and advanced signal processing algorithms, enabling the accurate, stable, and reliable collection and analysis of data. The research findings demonstrate that the system can accurately detect and analyze the electrophysiological signals of tomato plants, assisting in the assessment of their responses to varying environmental conditions. With its flexible design, cost-effectiveness, and scalability, the system can be applied to a wide range of crops, contributing to improved agricultural productivity. This study presents significant potential in smart agriculture, supporting early detection of adverse environmental impacts, optimizing cultivation, and promoting sustainable resource management in the context of climate change.

XÂY DỰNG HỆ THỐNG NHÚNG GIÁM SÁT TÍN HIỆU ĐIỆN SINH LÝ TRÊN CÂY CÀ CHUA CHO NÔNG NGHIỆP THÔNG MINH

Phạm Văn Khoa[1*], Đinh Tiến Dũng[1], Nguyễn Ngô Lâm[1], Chi-Chia Sun[2]
[1]*Trường Đại học Sư phạm Kỹ thuật Thành phố Hồ Chí Minh, Việt Nam*
[2]*Trường Đại học Quốc gia Đài Bắc, Đài Loan*

THÔNG TIN BÀI BÁO

Ngày nhận bài: **05/02/2025**
Ngày hoàn thiện: **13/4/2025**
Ngày đăng: **15/4/2025**

TỪ KHÓA

IoT
Điện cực
Điện sinh lý cây cà chua
Cảm biến
Hệ thống nhúng

TÓM TẮT

Nghiên cứu này được thực hiện nhằm giải quyết vấn đề ô nhiễm môi trường ngày càng gia tăng, gây ảnh hưởng tiêu cực đến cây trồng nông nghiệp, đặc biệt là cây cà chua – một loại cây có giá trị cao được trồng rộng rãi tại Việt Nam. Mục tiêu của nghiên cứu là phát triển một hệ thống nhúng thông minh sử dụng vi điều khiển tích hợp với mạch điện tử và các điện cực để theo dõi các phản ứng sinh lý của cây cà chua trước các yếu tố môi trường như ánh sáng, nhiệt độ và độ ẩm. Hệ thống này được trang bị các bộ khuếch đại và thuật toán xử lý tín hiệu cho phép thu thập và phân tích dữ liệu một cách chính xác, ổn định và đáng tin cậy. Kết quả nghiên cứu cho thấy hệ thống có khả năng phát hiện và phân tích chính xác các tín hiệu điện sinh lý của cây cà chua, hỗ trợ đánh giá phản ứng của cây đối với sự thay đổi của môi trường. Với thiết kế linh hoạt, chi phí hợp lý và khả năng mở rộng, hệ thống có thể được áp dụng cho nhiều loại cây trồng khác nhau, góp phần nâng cao năng suất nông nghiệp. Nghiên cứu này thể hiện tiềm năng to lớn trong nông nghiệp thông minh, hỗ trợ phát hiện sớm các tác động môi trường bất lợi, tối ưu hóa quá trình canh tác và thúc đẩy quản lý tài nguyên bền vững trong bối cảnh biến đổi khí hậu.

DOI: https://doi.org/10.34238/tnu-jst.11967

[*] Corresponding author. *Email: khoapv@hcmute.edu.vn*

1. Introducion

Climate change is one of the most pressing global challenges, significantly impacting agriculture and food security [1], [2]. Unpredictable fluctuations in temperature, humidity, and light can reduce crop yields and quality, leading to substantial economic losses in the agricultural sector. Among economically valuable crops, tomatoes are particularly sensitive to environmental conditions, making them highly susceptible to external stress factors [3], [4]. However, this sensitivity also makes tomatoes an ideal model plant for research, providing crucial insights into plant physiological responses to environmental changes.

In Vietnam, tomatoes are widely cultivated but are among the crops most severely affected by climate change and extreme environmental conditions, posing significant risks to farmers and the agricultural economy. Traditional farming methods primarily rely on manual adjustments of environmental factors based on farmers' experience. However, these approaches lack a strong scientific foundation, leading to inconsistent yields and inefficient resource utilization [5].

The development of smart agriculture technologies has introduced new approaches to monitoring plant physiology, particularly through sensor-based systems and IoT applications. Several previous studies have applied modern technology to track plant physiological responses. For example, Mazarei [6] pioneered the use of genetically modified plants as biosensors for pathogen detection, while Roger [7] demonstrated that plant electrophysiological signals can reflect changes in CO_2 levels, humidity, and temperature. Additionally, Hamann [8] proposed a bio-hybrid system integrating plants and robotics, opening new possibilities in plant biotechnology applications. However, most existing monitoring systems focus on single environmental parameters, such as soil moisture monitoring or disease detection, without providing a comprehensive analysis of plant responses to multiple environmental stressors. Furthermore, current plant monitoring technologies lack real-time adaptability, often requiring manual calibration or hardware modifications when applied to different crop types [9]. Developing a real-time, multi-parameter plant monitoring system using electrophysiological signal analysis remains largely unexplored.

This study aims to address these limitations by developing an advanced electrophysiological sensor system capable of continuously monitoring tomato plant responses to multiple environmental factors, including light, temperature, and humidity, in real time. The proposed system integrates a microcontroller, electronic circuits, and non-invasive electrodes to collect and analyze plant physiological signals accurately. Unlike traditional monitoring systems, this design features a dynamic signal amplification mechanism, enabling real-time sensitivity adjustments without requiring hardware modifications. This advancement allows the system to be highly adaptable and scalable, making it suitable for various crop types without major hardware changes.

Furthermore, by incorporating advanced signal processing algorithms, the system enhances data accuracy, noise reduction, and feature extraction, ensuring reliable plant physiology monitoring. The combination of real-time electrophysiological signal tracking, AI-based predictive analysis, and IoT connectivity establishes this system as a groundbreaking solution for smart agriculture, enabling early stress detection, optimized resource management, and enhanced crop resilience in changing environmental conditions.

2. Research Methods

This study develops an embedded electrophysiological sensor system to monitor tomato plant responses to environmental factors. The system utilizes Ag/AgCl electrodes, a programmable gain amplifier (PGA), an STM32 microcontroller, and a digital signal processor (DSP) to ensure high-accuracy signal acquisition and processing.

The research methodology consists of three main stages. First, parameter identification and system design are conducted through an extensive literature review to ensure that the selected components — such as electrodes, sensors, and amplification circuits — are appropriate for capturing the electrophysiological characteristics of tomato plants. Second, during the data collection phase, environmental parameters including light intensity, temperature, and humidity are systematically adjusted, while plant bioelectrical signals are recorded via electrodes and sensors. These raw signals are then processed using amplifiers and digital signal processing techniques, including Butterworth filtering, Wavelet Transform, and Kalman filtering, to suppress noise and enhance signal quality. Finally, in the system validation phase, the processed signals are compared with the recorded environmental conditions. Signal quality is evaluated using the signal-to-noise ratio (SNR), response consistency is assessed through cross-correlation analysis, and, where applicable, AI-based classification algorithms are employed to detect physiological stress patterns in the plants..

The results demonstrate that the system can accurately monitor the physiological responses of tomato plants, providing reliable real-time data for applications in smart agriculture. The paper is structured as follows: Section II discusses the plant electrophysiological system, Section III presents experimental results, and Section IV concludes the study.

Based on system requirements and the significance of the topic, this study proposes a plant electrophysiological signal monitoring system designed to optimize crop management in smart agriculture. The system utilizes sensors to monitor key environmental factors such as temperature, humidity, and soil moisture**,** providing real-time data on plant physiological responses**.** The system comprises the following main components, as described in Figure 1.

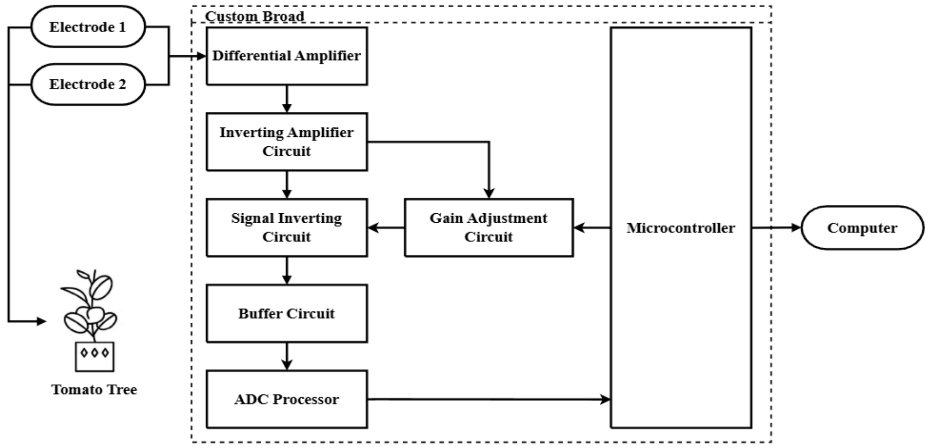


Figure 1. *Proposed Tomato Plant Monitoring System*

Electrodes capture bioelectrical signals from tomato plants to assess environmental conditions. The Custom Board filters noise, amplifies signals, and processes data before transmitting it to a computer. High-pass and low-pass filters refine the signal, which is then converted to digital format via an ADC. The computer displays real-time visual graphs and waveforms, enabling remote monitoring and timely decision-making. The hardware architecture follows a sequential processing flow, as illustrated in Figure 1.

- Electrodes capture bioelectrical signals from tomato plants.
- A differential amplifier enhances and filters the signals.
- An inverting amplifier and signal inversion circuit refine the signals to maintain accuracy.
- A gain adjustment circuit dynamically controls signal amplification.
- A buffer circuit stabilizes the signals before conversion.
- An ADC processor converts the analog signals into digital form.
- The microcontroller processes and transmits the data to a computer, where it is displayed as waveforms or graphs for easy monitoring and analysis.

This system is specifically designed for tomato plants, but its scalable architecture allows it to be adapted for various crop types, expanding its potential applications in smart agriculture.

2.1. Electrode

The electrodes play a crucial role in capturing the bioelectrical signals from tomato plants. These signals indicate the physiological and biochemical processes of the plant, such as water and nutrient transport or responses to environmental factors. Table 1 provides a basic overview of common plant electrode types used in experiments.

Table 1. *Three common types of electrodes in plant research*

Electrode Type	Definition	Common Applications	Key Features
Surface Electrode	An electrode placed on the surface of leaves, stems, or roots to record electrical signals from plant tissues.	Monitoring bioelectrical signals in response to light, mechanical stimuli, or environmental stress.	Made of Ag/AgCl or carbon. Easy contact, non-invasive.
Microelectrode	A very small electrode that measures electrical signals directly at the cellular or membrane level.	Recording membrane potential. Tracking intracellular ion flux. Studying ion transport or intracellular signaling in photosynthesis and physiological stress.	Very small tip (<1 µm), reduces noise. Made of glass or metal, high precision.
Ion-Selective Electrode	A specialized electrode for measuring the concentration of a specific ion in plant cell fluids or surrounding environments.	Analyzing ion transport across cell membranes. Studying root-soil interactions. Monitoring ions like H+, K+, Ca2+ in plant physiological responses.	High sensitivity to specific ions. Coated with an ion-selective membrane for precise detection.

The performance and accuracy of the electrodes depend on the material used. Common materials include: Au, which has high corrosion resistance, excellent conductivity, but is expensive; Ag/ AgCl, which offers high sensitivity, stability, and low noise, making it suitable for biological applications; and stainless steel, which is durable and cost-effective but has lower electrical conductivity compared to silver [12]. The electrodes used in this study are surface electrodes with metal probes coated with Au, Ag/ AgCl. These electrodes are inserted into the stem and leaves of the plants to capture bioelectrical signals effectively. Figure 2 illustrates the electrodes used in the study.

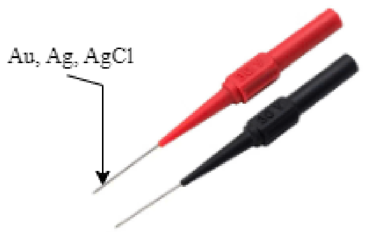


Figure 2. *Electrodes for Measurements*

2.2. Hardware design

The measurement system is designed to accommodate signal acquisition for various types of plants, with tomatoes as the focus in this project, ensuring scalability and flexibility. As shown in Figures 3, the system comprises the following main functional blocks: an amplification block, a gain adjustment block, an analog-to-digital signal conversion block, a microprocessor block, an Ethernet communication block, and the power supply block for the operational amplifier. This design ensures flexibility, allowing the system to connect with different types of agricultural plants without requiring hardware modifications.

a) Amplification block amplifies weak electrophysiological signals from the tomato plant. It includes differential amplifiers to reduce noise and improve signal clarity, utilizing the INA333 IC – a low-noise differential amplifier. Additionally, the block integrates filters (low-pass and high-pass) to eliminate unwanted frequencies [13].

b) Gain adjustment block allows fine-tuning of the amplification level to match the signal strength. It utilizes the IC AD5262BRUZ200 – an electronic potentiometer that enables flexible adjustment of amplification levels through control signals from the STM via the SPI protocol. This ensures that the signal remains within the optimal range for further processing [14].

c) ADC signal conversion block converts the amplified analog signal into a digital format using the AD7616 IC – a 16-bit ADC with low data offset, approximately 0.2 mV under ideal conditions and up to 2.5 mV at maximum. This capability supports high-precision digital analysis of physiological responses in plants [15].

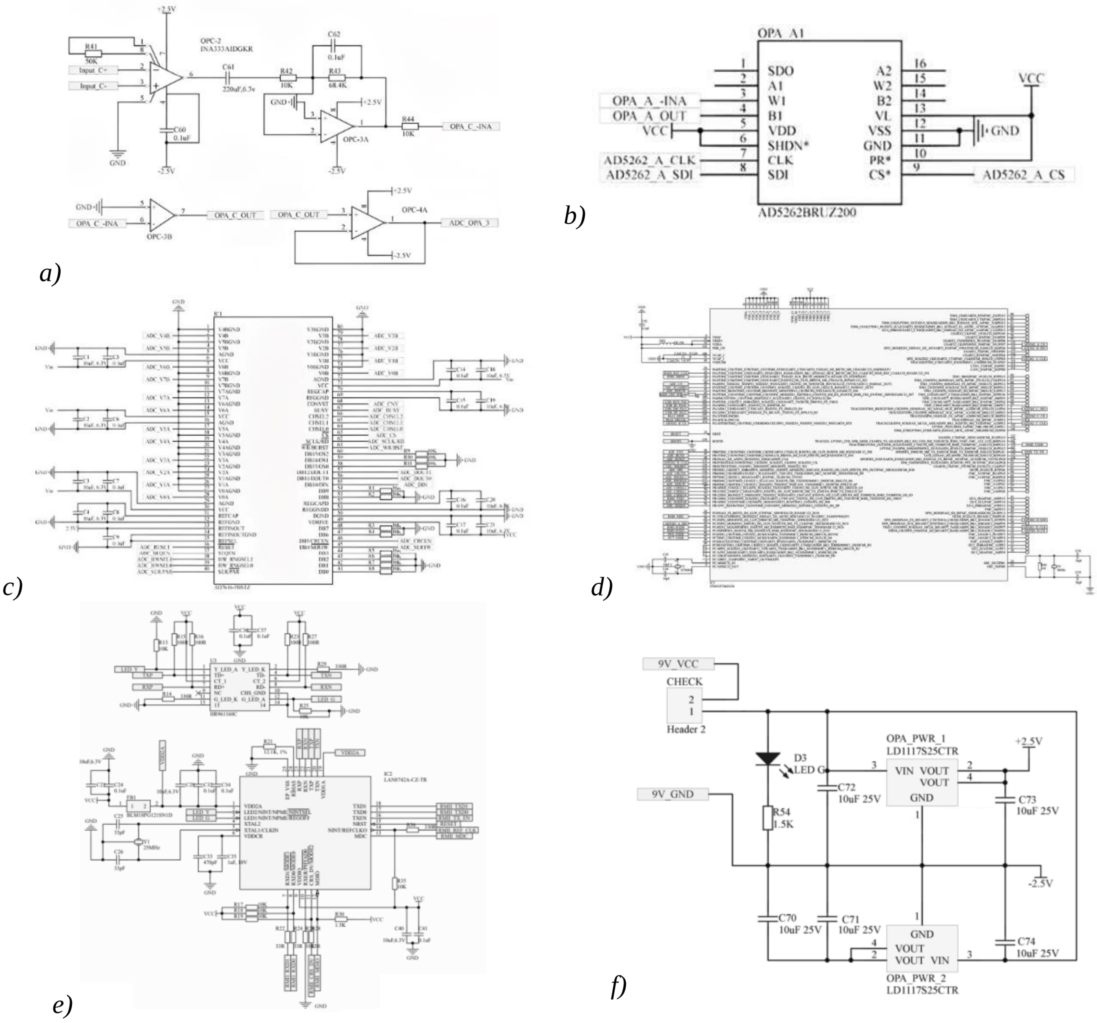


Figure 3. *Schematic diagrams: (a) Amplification block, (b) Gain adjustment block, (c) ADC signal conversion block, (d) Microcontroller block, (d) Microcontroller block, (e) Ethernet communication block, and (f) OPA power supply block*

d) Microcontroller block utilizing the STM32F746 chip, it is responsible for control, data processing, and communication with peripheral devices, ensuring the full functionality of the device. Additionally, the microcontroller supports Ethernet communication, enabling seamless data transmission to external systems [16].

e) LAN8742A-CZ-TR chip in the communication block, supports Ethernet transmission speeds of up to 1000 Mbps, providing a stable and fast connection between the physiological monitoring system and the computer, helping to prevent data loss and ensuring efficient real-time data transmission [17].

f) The OPA power supply block uses the LD1117S25CTR chip. An LDO voltage regulator with a maximum current of up to 800mA, it provides a stable ±2.5V power supply to the operational amplifiers, ensuring the precise and reliable operation of the signal amplification circuits [18].

2.3. Algorithm flowchart

The flowchart in Figure 4 illustrates the operation of the embedded system, utilizing the UDP communication protocol to ensure stable connectivity, accurate data collection, and efficient transmission. The system begins with an initialization phase, which includes configuring the Hardware Abstraction Layer (HAL), setting up the system clock, and initializing the UDP server. Once completed, the system transitions into the main loop, where it continuously monitors val_speed and val_mode to determine the operational status. At the "Start Connect" decision point, if the connection is not established (Start_Connect = 0), the system returns to the main loop to continuously check for changes. However, if the connection is successfully established, the system initiates data acquisition from sensors through an Analog-to-Digital Converter (ADC). The collected data is then processed using filtering algorithms to enhance signal accuracy and remove noise. After signal processing, the system extracts key features from the data, identifying crucial physiological responses of the plant. Finally, the processed data is transmitted to the server via UDP for further analysis. This algorithm ensures high accuracy, efficiency, and real-time adaptability. Additionally, the system can automatically detect anomalies, allowing it to re-enter the processing loop when inconsistencies are detected, ensuring data reliability and system stability. By providing real-time physiological data, the system enables farmers to monitor plant health effectively and respond promptly to environmental stress factors.

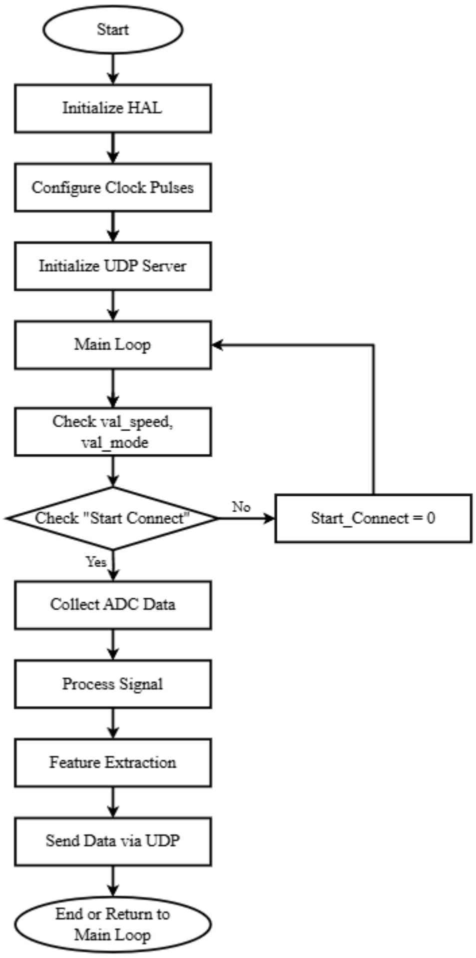
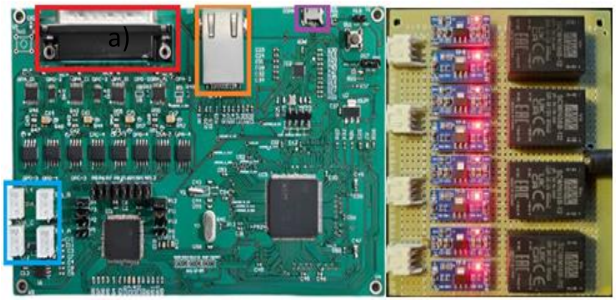


Figure 4. *Algorithm flowchart*

3. Experimental Results

3.1. Hardware model

Figure 5a illustrates the (Printed Circuit Board) PCB circuit after completing the hardware of the system for recording electrophysiological signals from tomato plants. The technical specifications are as follows: The STM32F746ZGT microcontroller serves as the main processor of the system, providing robust computational capability and diverse communication support. The power supply is designed to be flexible, including ±2.5V through an XH-2.54 connector for the amplifier blocks, and 5V via a Micro USB port for the microcontroller, ensuring stable power for the entire system. The system supports the LAN8742A-CZ-TR network interface, enabling Ethernet communication at speeds of 10/100 Mbps through an RJ45 port, allowing for fast and stable data transmission. Signal input from 8 electrodes is connected via a DB25 port, suitable for collecting multi-channel signals with high stability. The integrated ADC has a 16-bit resolution, providing high-precision signal measurement with a sampling rate of up to 1 million samples per second. The amplification factor of the system is flexible, adjustable from 20 to 400 times. The circles indicated in red, orange, purple, and blue highlight the positions of the DB25, RJ45, Micro USB, and XH-2.54 connectors, respectively, on the actual design. Figure 5b shows the actual product for providing ± 2.5V power for the OPA (Operational Amplifier) block, featuring four corresponding XH-2.54 connectors.



a) b)

Figure 5. *Printed circuit board circuits of the proposed system: a) Circuit board of the signal acquisition system, b) ± 2.5V power supply circuit board for the OPA*

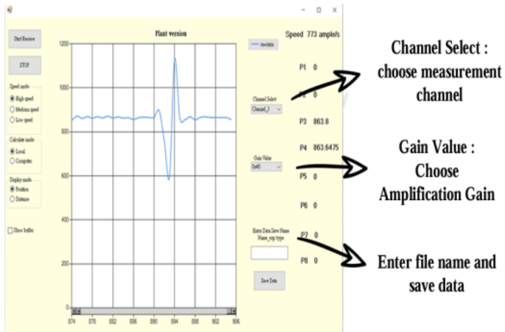


Figure 6. *Program interface for acquiring electrophysiological signals from tomato plants*

3.2. Program interface

The program interface for acquiring electrophysiological signals from tomato plants, illustrated in Figure 6, provides a visual tool for collecting, processing, and storing data. This interface is designed to display a graph showing the electrophysiological signal over time, allowing users to directly monitor the status and changes of the signal. It enables users to easily perform basic operations such as selecting the signal measurement channel, setting the signal amplification value and entering a file name to save the data. This interface helps users optimize the process of measuring and analyzing the electrophysiological signals of tomato plants effectively.

3.3. Perform signal acquisition from the tomato plant

The experiment monitored the electrophysiological signals of plants in a controlled environment. Figure 7 shows the setup, where sensors measured temperature and humidity to analyze plant responses. Data was collected over 3–6 hours, ensuring stability. Electrodes captured real-time signals, which were filtered, amplified, converted, and transmitted to a computer for graphical visualization.

Figure 7. *Tomato plant measurement setup*

Although this experiment focused on tomato plants, the system is designed to be adaptable for various plants. The temperature and humidity measurements provide valuable insights into how environmental conditions affect plant physiological activity, supporting the optimization of agricultural practices in smart farming applications.

3.4. Measurement results

Figures 8 and 9 present visual charts depicting temperature variations, focusing on differential voltage data in temperature detection and its effect on tomato plants. These experiments analyze temperature changes during the respiration process across three time intervals: night, midnight, and morning. Results reveal that while the temperature sensor records air temperature shifts, the differential voltage signal from the plant reacts uniquely. The signal indicates a sharp temperature drop from night to early morning, reflected by a negative voltage change, while in the morning, the temperature rises gradually with a positive voltage shift. Figures 10 and 11 illustrate environmental humidity changes and the response of the tomato plant. Figure 11 records differential voltage data, showing a stable low signal in dry conditions, which increases sharply when it rains, suggesting high humidity sensitivity in the plant.. Additionally, environmental humidity measurements confirm low humidity during dry periods and a significant rise when rain occurs [19].

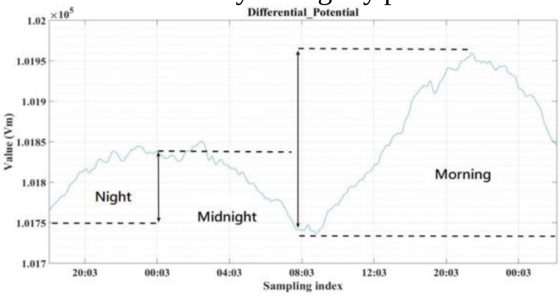


Figure 8. *Temperature detection*

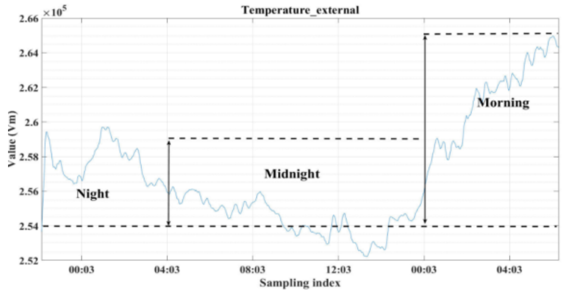


Figure 9. *Differential potential data of temperature detection*

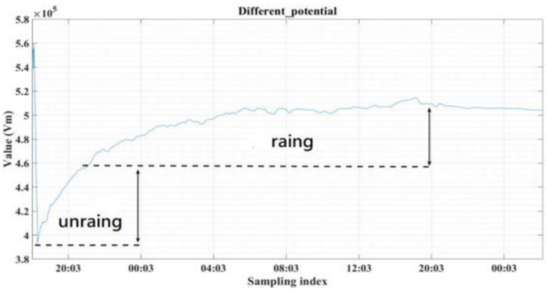


Figure 10. *Humidity detection*

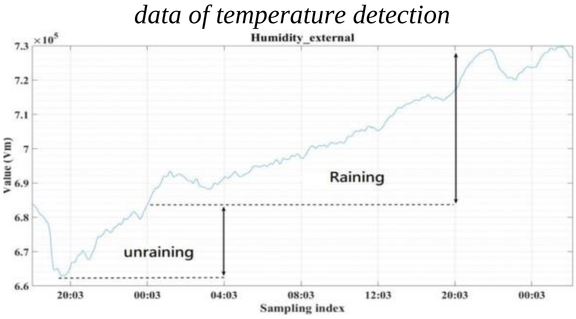


Figure 11. *Differential potential data of humidity detection*

4. Conclusion

This study introduces an embedded system for real-time monitoring of tomato plant electrophysiological signals, significantly enhancing accuracy in detecting physiological responses to environmental factors. By integrating a dual-stage amplification circuit, digital signal processing, and IoT-based monitoring, the system enables continuous tracking and data-driven decision-making, surpassing traditional monitoring methods. Experimental results validate the system effectiveness, demonstrating strong plant responses under specific conditions: temperature (104.12 mV – 105.60 mV) and soil moisture (550 mV – 575 mV). These findings highlight the system's potential in optimizing plant health monitoring by enabling early detection of stress factors and enhancing agricultural management efficiency. Despite its advantages, signal noise and environmental variability remain challenges to address. Future improvements should focus on optimizing signal processing algorithms and integrating AI for predictive modeling, enhancing adaptability across different crop types. By advancing precision agriculture, this system contributes to sustainable farming practices, optimizing resource usage and increasing crop resilience to climate change.

Acknowledgements

This work belongs to the project in 2025 funded by Ho Chi Minh City University of Technology and Education, Vietnam.

REFERENCES

[1] S. Bernardes, "A global multimodel analysis of predicted changes in plant water use efficiency and primary productivity in the 21st century," *in Proc. IEEE Int. Geosci. Remote Sens. Symp*. (IGARSS), Jul. 2018, pp. 7648–7651.
[2] O. K. Atkin and M. G. Tjoelker, "Thermal acclimation and the dynamic response of plant respiration to temperature," *Trends Plant Sci*., vol. 8, no. 7, pp. 343–351, Jul. 2003.
[3] L. D. Vassilis, A. Migeon, M. Navajas, M.-S. Tixier, and M. C. Stavrinides, "Impacts of climate change on tomato, a notorious pest and its natural enemy: Small scale agriculture at higher risk," *Entomology, Environ. Res. Lett*., vol. 14, 2019, Art. no. 084041.
[4] Q. Khan, Y. Wang, G. Xia, H. Yang, Z. Luo, and Y. Zhang, "Deleterious effects of heat stress on the tomato, its innate responses, and potential preventive strategies in the realm of emerging technologies," *Metabolites*, vol. 14, no. 5, 2024, Art.no. 283.
[5] A. G. Volkov and V. S. Markin, "Phytosensors and phytoactuators," in *Plant Electrophysiology*. Springer, 2012, pp. 173–206.
[6] M. Mazarei, I. Teplova, M. R. Hajimorad, and C. N. Stewart, "Pathogen phytosensing: plants to report plant pathogen infections," *Sensors*, vol. 8, no. 4, pp. 2628–2641, 2008.
[7] R. D. Rogers, K. R. Seddon, and S. Volkov, "Green Industrial Applications of Ionic Liquids," vol. 92,. Dordrecht, The Netherlands: Springer, 2012. [Online]. Available: https://link.springer.com/book/10.1007/978-94-010-0127-4. [Accessed Feb. 5, 2025].
[8] H. Hamann *et al.*, "Flora robotica—An architectural system combining living natural plants and distributed robots," *arXiv:1709.04291*, 2017.
[9] M. Wahby *et al.*, "A robot to shape your natural plant: The machine learning approach to model and control bio-hybrid systems," in *Proc. Genetic Evol. Comput. Conf.*, Jul. 2018, pp. 165–172.
[10] O. Sakata, M. Iwashita, Y. Satoh, and Y. Suzuki, "Measurement of electric potential of a plant using electroconductive cloth sensor," in *Proc. 7th IIAE Int. Conf. Intell. Syst. Image Process*, 2019, pp. 1–6.
[11] Z.-Y. Wang *et al*., "Multi-channel system for simultaneous in situ monitoring of ion flux and membrane potential in plant electrophysiology," *IEEE Access*, vol. 7, pp. 4688–4697, 2019.
[12] J.-T. Yeh, C.-Y. Hsiao, H.-W. Lee, and C.-F. Kuo, "Comparison between Different Configurations of Reference Electrodes for an Extended-Gate Field-Effect Transistor pH Sensor," *ACS Omega*, vol. 10, pp. 8433-8439, 2025.
[13] Texas Instruments, "INA333: Low-Power, Zero-Drift, Precision Instrumentation Amplifier," datasheet, Rev. C, Jul. 2019. [Online]. Available: https://www.ti.com/lit/ds/symlink/ina333.pdf [Accessed Feb. 5, 2025].
[14] Analog Devices, "AD5260/AD5262: 1-/2-Channel 15 V Digital Potentiometers Data Sheet," Rev. A, 2009. [Online]. Available: https://www.analog.com/media/en/technical-documentation/data-sheets/AD5260_5262.pdf. [Accessed Feb. 5, 2025].
[15] Analog Devices, "AD7616: 16-Channel DAS with 16-Bit, Bipolar Input, Dual Simultaneous Sampling ADC Data Sheet," 2018. [Online]. Available: https://www.analog.com/media/en/technical-documentation/data-sheets/AD7616.pdf. [Accessed Feb. 5, 2025].
[16] STMicroelectronics, "STM32F746ZGT6: High-performance Arm Cortex-M7 MCU with 1 Mbyte Flash, 216 MHz CPU, Art Accelerator, datasheet," Rev. 9, Mar. 2019. [Online]. Available: https://www.st.com/resource/en/datasheet/stm32f746zgt6.pdf. [Accessed Feb. 5, 2025].
[17] Microchip Technology Inc., "LAN8742A-CZ-TR: Ethernet Transceiver Datasheet," 2013. [Online]. Available: https://www.alldatasheet.com/datasheet-pdf/view/884756/MICROCHIP/LAN8742A-CZ-TR.html. [Accessed Feb. 5, 2025].
[18] STMicroelectronics, "LD1117S25CTR: Low Dropout Regulator Datasheet," 2025. [Online]. Available: https://www.alldatasheet.com/datasheet-pdf/view/395661/STMICROELECTRONICS/LD1117S25CTR.html. [Accessed Feb. 5, 2025].
[19] C.C. Sun, F.C. Chan, A. Ahamad, and Y. H. Yao, "Improved Natural Plant Electrophysiology Sensor Design for Phytosensing System," *IEEE Transactions on Instrumentation and Measurement*, vol. 72, pp.1-10, 2023.